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**A degree is not enough: a quantitative study of aspects of
pre-service science teachers' chemistry content knowledge**

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Abstract

Aspects of chemistry content knowledge held by 265 UK-based pre-service teachers were probed using 28 diagnostic questions in five chemistry concept areas, *Particle theory and changes of state*, *Mass conservation*, (taught to 11 – 14 year olds) and *Chemical bonding*, *Mole calculations* and *Combustion reactions* (taught to 14 – 16 year olds). Data were collected over six years from academically able science graduates starting a full-time, university-based teacher education programme of one academic year duration. PSTs in three sub-cohorts (“chemists”, “physicists” and “biologists” on the basis of their undergraduate degrees) demonstrated similar levels of content knowledge for *Particle theory and changes of state* and *Mass conservation*. Biologists demonstrated statistically significantly weaker understanding than chemists and physicists in *Chemical bonding*, *Mole calculations* and *Combustion reactions*. 44 “triads” each comprising one chemist, physicist and biologist, matched by academic and personal backgrounds, showed chemists out-performed biologists and physicists in *Chemical bonding* and *Combustion reactions*. The findings suggest non-chemists’ content knowledge is insufficient for teaching these chemistry concepts in high schools, despite their possession of “good” Bachelor of science degrees. These data have implications for science teacher education, including how best to prepare science graduates from diverse backgrounds for teaching specialist science subjects to 11- 16 year olds.

**A degree is not enough: a quantitative study of aspects of
pre-service science teachers' chemistry content knowledge**

Ensuring that all children are taught by highly qualified teachers is regarded as a key objective for education systems worldwide. For example, the European Commission's Strategic Framework for Education and Training 2020 (2013) states "that high-quality pre-primary, primary, secondary, higher and vocational education and training are fundamental to Europe's success". The Framework includes "improving the quality and efficiency of education and training" as an aim, setting a benchmark figure of less than 15% of 15 year-olds possessing "insufficient abilities" in reading, mathematics and science by 2020. However, an earlier report finds that science teacher shortages at 15% or more of available positions are apparent in fourteen of thirty-three EU countries submitting data (European Commission, 2012). This report also notes that PISA (Organisation for Economic Co-operation and Development, OECD, 2010) data shows "many students in Europe are being taught in schools where teaching is hindered by lack of qualified teachers in core subjects, including science" (p 14 and p 113). Similarly, the United States aims to create schools that enable all children to learn regardless of background. This is enshrined in *No Child Left Behind*, a re-formulation of the country's 1965 Elementary and Secondary Education Act (US Department of Education, 2001). Darling-Hammond (2010) comments that to implement this policy requires addressing longstanding inequalities in student achievement, so accountability should focus on "ensuring competence of teachers and leaders [and] the quality of instruction" (p 9). In Australia, professional standards emphasise the "knowledge, practice and professional engagement" expected of teachers during their careers. Achieving equity for all students is also foremost, as Dinham (2010) notes, "The biggest equity issue in Australian education today [is] each student having quality teachers and quality teaching in schools" (p 12).

The issue is also pertinent in less industrialised nations. For example, South Africa recorded scores amongst the lowest of all participating nations in PIRLS (IEA, 2006) and TIMSS (1998), declining to participate in more recent surveys. *TeachSouth Africa* (2013) recognises that improving education quality will aid economic development and help address inequalities. The organisation aims to raise the quality of teachers in South African schools in order to “...help close the achievement gap [and prepare] a generation of learners to be better prepared for university and the workplace.”

How teachers may attain the knowledge required to achieve these high stake and status objectives is debated. For example, in England and Wales specifically, the UK government is promoting school- rather than university-based teacher education, on the basis that a “good” graduate possesses sufficient knowledge to enable him/ her to teach well without a lengthy (and expensive) university course (DfE, 2010). Similarly, Ball (2010) notes that in the US, “The gateway to teaching has been widening,” as a variety of “alternative” options is now available to enter the profession. The European Union (EU) report (op cit, 2012) shows that among EU nations, a main pre-requisite for teaching is holding a completed upper secondary examination certificate. About half of EU nations offer initial teacher education for lower secondary students (11-16s) at Bachelor’s degree level. The remainder provide Master’s level teacher education. Thus, variation in length and the nature of teacher education exists internationally. In Ball’s (2010) terms, collectively we “lack a reliable system for preparing those who want to teach” (p 8).

This paper contributes evidence and a potential strategy to discussion about how to ensure high quality science teachers are trained. Data presented reveal that recruiting highly qualified, academic graduates is not an automatic precursor to ensure high quality teachers, as weaknesses in their understanding of basic science concepts, in this case, a range of chemistry concepts, is apparent. Variety within the PST sample permits comparison between knowledge held by graduates of different scientific disciplines. Although

differences may be expected between, say a biologist and a chemist, these matter, because, for a variety of reasons, many science teachers teach “out-of-field” topics, that is, aspects of science in which their content knowledge background is limited. Teachers lacking understanding of fundamental concepts of a science are unlikely to promote students' accurate learning, so will fail to meet the high standards national policies expect. The study offers a strategy for diagnosing and developing the quality of pre-service teachers' (PSTs) content knowledge (CK) to help provide a secure basis for ensuring students learn concepts accurately and scientifically.

Theoretical Framework

Theoretically, the study lies within Shulman's (1987) paradigm in which content knowledge is one of seven components of a teacher's knowledge base. Shulman and colleagues (Grossman, 1990; Wilson, Shulman & Richert, 1987) studied novice teachers at length, establishing that personal understanding of subject matter alone was insufficient for success. Teachers require a “specialised” understanding that permits fostering of understanding in their students. Shulman (1986) argued this goes beyond knowing facts and concepts, but includes organizing principles and structures, as well as “rules” governing what is legitimate to say or do when working in a specific subject field. The notion of “why”, is, for a teacher, as significant as “what”. Schwab (1978) uses the term “syntactic” knowledge to describe the logical structures of a discipline, and “substantive” knowledge to represent its concepts and facts. The current paper highlights differences in substantive knowledge about chemistry concepts (that teachers may reasonably be expected to know) in a population of graduates from a range of scientific disciplines. “Content knowledge” is a convenient term used by Shulman (op cit) and subsequently in the literature to describe this (for example, Ball, Thames & Phelps, 2008). As this paper is about chemistry, the abbreviation “CCK” represents “Chemistry Content Knowledge”.

The connection to teaching science also requires explanation. Shulman (1986) coined the term "pedagogical content knowledge" (PCK) as:

"The most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the most useful ways of representing and formulating the subject that make it comprehensible to others ... Pedagogical content knowledge also includes an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons." (p 9)

To develop good "representations" of a subject that prompt student learning about science concepts, teachers must know about students' conceptions. This is different from the knowledge about a science as part of a degree. Deng (2007) refers to "school" knowledge of a science, noting how this differs from academic knowledge. Teachers need to learn school science as part of their content knowledge for teaching. Knowing students' possible and potential misconceptions and misconceptions is an essential part of this. Ensuring high quality teachers means ensuring high quality content knowledge. This paper shows that holding an academic degree in a science does not mean a graduate has high quality content knowledge of the type needed to teach students effectively. A teacher with content knowledge that includes personal misconceptions about a science concept is hardly likely to be able to develop high quality PCK. By revealing the misconceptions graduates have about basic chemistry concepts, this study contributes to our understanding of content knowledge held by novice science teachers, and points to what teacher education must do to ensure quality.

Extant literature uses various terms to describe understandings of science concepts

("misconception", "alternative conception", "naïve ideas", "pre-science", "prior knowledge", etc). To maintain consistency with literature on teachers' knowledge base, a decision was taken to use "misconceptions" to describe incorrect or faulty responses to the probes.

Literature Review

The Novice – Expert Shift

PSTs enter teaching as novices. They have some content knowledge, and perhaps some, limited, teaching experience, but are not "expert" teachers. Research indicates that novices and experts differ in the ways they approach teaching. For example, Geddis, Onslow, Beynon & Oesch (1993) examined novice and experienced teachers teaching isotopes. Novice chemistry teachers adopted "transmission" mode. Their strategy was to assume that giving a short lecture based on their accurate personal content knowledge followed by a set of sample calculations would ensure all students learned the concept. They expressed surprise when students failed to understand aspects such as why atomic masses could be fractional, and how different isotopes were represented in fractional atomic mass values. In contrast, an experienced teacher used his content knowledge as a tool to help build up students' understanding of topic components gradually. He adopted a "sideways" approach, starting at a point which seemed far removed from the central concept. His strategy was to help student understand key principles, such as mathematical ideas, that led to developing sound understanding. Although both the novice and expert teachers held similar content knowledge, only the expert was able to generate student understanding. His PCK was well-developed, taking students' understandings into account and melding these with his own content knowledge to devise strategies that had positive learning outcomes. Clearly, the expert teacher had specialist knowledge that the novices had yet to

learn. Hill & Ball (2009) make similar points about mathematics education, noting, "...conventional content knowledge seems to be insufficient for skillfully handling the mathematical tasks of teaching" (p 69).

To become "expert" in teaching requires a combination of learning new knowledge, such as how students learn science and the difficulties they experience alongside practice. Author (2009a) showed that initially, PSTs asking for support from more experienced, or "expert" teaching in preparing lessons generally experience greater success in generating learning. Most often, this occurs when teaching out-of-field topics they have not studied since school. When teaching within specialism, PSTs experienced a tacit expectation to "know" their subject, which prohibits their asking for help.

In their longitudinal study, Arzi & White (2007) illuminate factors contributing to changes in teachers' CK over a seventeen year period, during which time the participants made the transition from novice to experienced (but not necessarily "expert") teachers. They report that teachers' unused CK was forgotten and little new knowledge learned. Teachers integrated and understood key concepts over time, but the school curriculum replaced their university science degrees or school qualifications as the main long-term organiser and CK source. The novices in Geddis et al's (1993) study relied on their degree knowledge to teach the topic. Arzi & White (op cit) showed that as teachers develop the ability to teach curriculum knowledge, this is at the expense of academic knowledge. De Jong, Acampo & Verdonk (1995) point to a possible consequence arising from over-familiarity with curriculum knowledge. They studied two experienced teachers teaching reduction-oxidation ("redox") reactions. They found the teachers introduced unnecessary concepts, ignored misconceptions and offered superficial explanations. The authors conclude that rather than teaching to students' needs, these teachers taught at the highest level, reflecting CK and curricular knowledge familiar to them (p 1108).

Although they were well-qualified and experienced, neither factor guaranteed excellence. De Jong, Acampo & Verdonk 's data support that of Tobin & Fraser (1990), who found experienced teachers failed to recognise students' misconceptions and did not ask challenging questions. In England and Wales, inspectors representing the Office for Standards in Education (Ofsted) report similar findings (Ofsted, 2011). These findings mean that developing good teachers requires something more than ensuring they have Bachelors' degrees and appropriate classroom experience. They need support to develop PCK that generates student learning.

How content knowledge impacts on PCK for teaching within and outside science specialism

Research on the transition from novice - expert teacher reported above reveals that a gap exists in developing teachers' knowledge. This gap constitutes lack of understanding about how to ensure novices become *expert* teachers, rather than just experienced teachers. To help fill this, we need to know more about how content knowledge impacts on PCK for teaching. Hill & Ball (2009) raise the same point about mathematics education, stating there is a need "to identify those aspects of mathematical knowledge for teaching that show the greatest potential for improving learning" (p 71).

Current, relatively extensive research evidence shows a teacher's content knowledge impacts on the quality of his/her classroom practice. For example, Carlsen (1993) found novice biology teachers posed higher order questions and used more active learning strategies when teaching topics they knew well. Conversely, Finlayson, Lock, Soares & Tebbutt (1998) found UK PSTs expressed difficulties teaching their non-specialist science subjects, often due to unfamiliarity with subject knowledge and resources. These authors note PSTs' confidence for teaching unfamiliar topics rose after doing this once: they conclude novice teachers aspire to "get by", rather than ensure students' understanding.

Other studies have investigated how experienced teachers respond when asked to teach topics outside their specialist subjects. For example, Hashweh (1987) investigated how CK impacts on experienced teachers' PCK, finding biology and physics teachers' subject knowledge influenced how s/he used a textbook to enact the curriculum. For topics in which their content knowledge was good, teachers detected students' preconceptions, dealt with general class difficulties appropriately, and interpreted students' incorrect comments correctly. In a more general study of teachers' practices, Sanders, Borko & Lockard (1993) investigated similarities and differences in experienced science teachers working within and outside specialism. In within specialism lessons, teachers identified students' questions and responded to unexpected events effectively, ensuring positive learning outcomes were achieved. Outside specialism, teachers behaved "like novice teachers" (p 723), responding poorly to students' questions and teaching lessons of inconsistent quality. Content knowledge limitations were apparent in outside specialism lessons. Gess-Newsome & Lederman (1995) report similar results in four experienced biology teachers, noting "the level of content knowledge had a significant impact on how content was taught" (p 317). Finally, K  p  ly  , Heikkinen & Asunta (2009) probed teachers' content knowledge for teaching photosynthesis and plant growth, finding those with "expert" levels of knowledge handled students' conceptual problems more readily and planned lessons with better attention to content than teachers with weaker knowledge. K  p  ly   et al support Gess-Newsome & Lederman (op cit), noting that teachers require a minimum level of content knowledge to be competent.

However, these findings serve only to illustrate the gap between content knowledge and PCK. The field has achieved a description of the way CK impacts on PCK, although this is far from systematic in terms of covering all aspects of science taught to all ages. Although studies inevitably make

recommendations, precise solutions for the best methods of promoting development of PCK that generates students' learning are hard to find.

Teachers' Chemistry Content Knowledge (CCK)

In this third section literature showing evidence of the quality of teachers' chemistry content knowledge is reviewed. Compared to research on students' understandings of chemistry concepts (Author, 2004), relatively little work offers insights into teachers' or even graduates' understandings. of the work that exists, more is devoted to primary (elementary) than secondary (high) school teachers' thinking about science concepts. Generally, research reveals that teachers' misconceptions are identical but fewer in number to those of their students (for example, Wandersee, Mintzes & Novak, 1994; Carré, 1993; Lloyd, Smith, Fay, Khang, Kam Wah & Sai, 1998; Schoon & Boone, 1998).

Research probing ideas about particles, conservation of mass and changes of state reveals the consistent finding that teachers explain the behaviour of substances using observable, macroscopic phenomena, not microscopic properties of particles. For example, Kruse & Roehrig (2005) report secondary science teachers using macroscopic language to describe particle behaviour. Primary teachers may ignore particle ideas completely when explaining changes in water and ice (Roth, 1992; Kruger & Summers, 1989). Conservation and orderly organisation of particles are ignored in primary teachers' drawings of atomic or molecular arrangements (Gabel, Samuel & Hunn, 1987). Lucille (2000) showed that although a majority of pre-service primary teachers understood regular and irregular molecular packing arrangements in ice and steam, some suggested molecules in liquid water were also arranged regularly.

Research on state changes shows a similar tendency to ignore microscopic features of particle behaviour. For example, Lucille reports only around 12% of pre-service primary teachers understood state changes correctly, many ignoring intermolecular bonds and energy. Rice (2005) found more than 50% of 400 pre- and 70 in-service elementary teachers suggested oxygen boils, that is changes from liquid to gas, at 100 °C; only 4% explained correctly what a “molecule” is; and 74% knew an electron is smaller than an atom. Other work in this area includes that of Lin, Cheng & Lawrenz (2000) who report teachers and students sharing similar misconceptions about gases and misusing gas laws; and Burgoon, Heddle & Duran (2010) who found that 35% of about 100 teachers of 9 – 10 year olds thought gases were lighter than solids or liquids, matching 9 – 15 year olds' views reported by Stavy (1990). Pre-service elementary teachers' understandings of vapour pressure, studied by Canpolat, Pinarbasi & Sözbilir (2006), showed common misconceptions that liquids need to be heated to vapourise; vapourisation starts when a liquid boils; and that vapour pressure depends on the amount and volume of liquid present.

International studies investigating teachers' understandings of more advanced chemical concepts reveal over-reliance on partially correct and incorrect rote learned statements and misinterpretation of taught information. For example, Coll & Taylor (2001) found chemistry undergraduates and graduates held the perception that any of metallic, ionic and covalent bonds are “weak” (p 177); interchanged “chloride” and “chlorine” when describing ionic compounds; and suggested that intermolecular bonds are present between “molecules” of ionic compounds. In South Africa, Bradley & Mosimege (1998) found no PSTs gave a “completely satisfactory” drawing of the particles present in an aqueous solution of hydrochloric acid. Few showed hydroxonium ions or water molecules, others showed hydrogen ions as a vapour above the acid, or drew hydrogen chloride molecules. Thirdly, in a Singaporean study (Kwen, 2000) probing understanding about five different

simple chemical reactions, most PSTs stated the “octet rule drives chemical reactions” (p 28), or thought externally applied heat or a chemical in the reaction itself was the driving force.

Studies of experienced teachers' understandings of chemistry also show misconceptions. Examples include Banerjee (1991), who explored knowledge of chemical equilibrium, finding 49% of teachers and 35% of students confuse rate and extent of a reaction, and reason that if the temperature of an exothermic reaction decreases, the rate of the forward reaction will increase. Queílez-Pardo & Solaz-Portolés (1995) found teachers and students misunderstood Le Chatelier's Principle, and that a teacher's conceptions might influence strategies used by a student in solving problems.

Extant research indicates broad agreement that teachers' content knowledge is inconsistent in quality. Even experienced teachers hold misconceptions about some concepts they are expected to teach. Ball, Thomas & Phelps (2008) comment: “Teachers must know the subject they teach... there may be nothing more foundational to teacher competency. The reason is simple: Teachers who do not themselves know a subject well are not likely to have the knowledge they need to help students learn this content. At the same time, however, just knowing a subject well may not be sufficient for teaching.” (p 404) Collectively, research evidence suggests that to achieve the high expectations of national and international education policymakers, systematic and reliable analysis of teachers' content knowledge and strategies for developing both this and PCK are required. Although Abell (2007) points out that other teacher knowledge may mediate the impact of CK on PCK, there is overwhelming agreement that the bar for “quality” CK is and should be set high. Borko (2004) states:-

“..teachers must have rich and flexible knowledge of the subject they teach... understand the central facts and concepts of the discipline, how these ideas are connected and the processes used to establish new knowledge and determine the validity of claims” (p 5).

Similarly, Khourey-Bowers and Fenk (2009) note that teachers need:-

“...broad and deep .. subject specific knowledge, awareness of common alternative conceptions and ... scientific models [that] can provide rich learning opportunities for their students..” (p 437 – 8)

For public schools to have high quality science teachers, meeting these criteria is reasonable. However, pragmatically, Deng (2007) points out that school and academic science differ logically, socially, psychologically and epistemologically. Teachers presenting for training with degrees in various aspects of science must master how school science interprets their chosen specialism, that is, learn content knowledge appropriate for teaching, in this as well as their non-specialist subjects.

Research Questions

The research questions are:-

1. What understandings and misconceptions about selected chemistry concepts are held by PSTs?
2. What differences are found in understandings and misconceptions between PSTs with backgrounds in biology, chemistry and physics?

Each is based on a hypothesis: first, PSTs have a range of understandings and misconceptions about high school chemistry concepts; and second, specialist chemists' responses are likely to be more scientifically accurate than those of biologists or physicists. Both have implications for strategies to improve the overall quality of teachers' CCK.

Context for the Study

The study took place in a (public) university in north-east England. 265 participants were

recruited over six years (2005 – 2010, 35 - 52 per year) as PSTs on a ten-month (September – June) full-time teacher education programme (a Postgraduate Certificate in Education, PGCE) divided time-wise 2:1 between schools: university. PSTs must meet basic Government-set criteria to apply for a training place, which include holding 16+ qualifications in English, Mathematics and Sciences, and a Bachelor's degree in a subject related to the National Curriculum subject to be taught. At the university where the study took place, applicants' personal qualities, such as resilience and flexibility in thinking are probed at interview, alongside the ability to write about a scientific topic clearly; scientific knowledge about concepts within and outside their degree subjects; and their motivation for becoming teachers. About half of all applicants are rejected. More applicants are biologists than physicists, creating informal competition, as places overall and thus for PSTs in each subject discipline are limited. This means academic standards for biologists are higher than for physicists. Few applicants have degrees in biology, chemistry or physics as "pure" subjects. Those classified as biology specialists have degrees in physiology, marine biology, ecology, genetics, microbiology, biomedical sciences, medicine, veterinary medicine, dentistry or environmental science; those aiming to be chemistry specialists studied biochemistry, color chemistry, forensic science, pharmacology, pharmacy, environmental chemistry or geology; and physics specialists have backgrounds in astronomy, astrophysics, theoretical physics, mechanical engineering or geophysics. Grossmann, Shulman & Wilson (1989) point out that degrees vary in quality, while content, as the above lists suggest, bear little resemblance to school science.

The PST Sample

The PSTs were a convenience sample, but this aids the present study, since all were recruited to the teacher education program according to identical criteria (see above) and procedures annually, by the same academic staff. Recruitment numbers were 38 (in 2005 – 2006); 35 (2006 – 2007); 47 (2007 –

8); 52 (2008 – 9); 48 (2009 – 10) and 45 (2010 – 11). In 2006 – 7 seven PSTs were absent on data collection day. Other variance occurred because recruitment numbers are varied annually due to Government controls on teacher numbers. Table 1 shows background characteristics of 265 PSTs. About 55% were classified on the basis of their degree backgrounds as biologists, 29% chemists, and about 17% physicists. About two-thirds were aged 25 or under, suggesting teaching was their first career choice. The remainder, including about 20% aged 30 or over, had had businesses; worked in science-based industries or academia, medicine, nursing or veterinary medicine; held non-scientific roles, such as administrators in government departments; or looked after young children.

[Insert Table 1 Here]

Respondents were academically well-qualified for teaching. Table 1 indicates about 90% hold degrees at 2:2 level ¹or above while 54% held degrees graded 2:1 or better. Over 60% of biologists held 2:1 or 1st class degrees, while around 40% of chemists and physicists did so. About 20% also held subject-based Masters or research doctorates. The gender distribution shows 54% were female and 46% male. Females dominated the biologists, while most physicists were male. Anecdotal evidence from other teacher educators suggests these PSTs' academic backgrounds are above average, while subject specialist, age and gender distributions are typical. Ethnically (data collected informally) the sample comprised approximately 95% Caucasians or other Europeans (for example, Spanish, Greek, Irish), 5% Asians (Chinese, Indian, Pakistani) and black Africans (Nigerian).

The diagnostic test

PSTs' understandings of five concept areas of chemistry (particles and change of state; conservation of mass in reactions; chemical bonding; mole calculations and combustion reactions)

¹ UK undergraduate degrees are awarded in five grades: "First" (Equivalent to secured marks 70+ / US GPA 4.00 / German "Outstanding" / Australian "High Distinction"); "2:1" (60-69 / GPA 3.3-3.9 / Substantially above average / Distinction); "2:2" (50 – 59 / GPA 3.0 – 3.2 / Good average / Credit); "Third" (40-49 / GPA 2.3 – 2.9 / Average / Pass); and "Ordinary" (35 – 40 / 2.0 – 2.2 / Barely meets requirements / Fail)

based on their responses to 28 short diagnostic probes (Barker, 1995; Appendix 1) are presented.

Rather than utilising a holistic test probing many areas of chemistry perhaps only once each, a strategic choice was made to investigate a limited selection using several probes for a smaller number. Concepts common to the current England and Wales Science National Curriculum (DfES, 2004) for 11 -16s were selected, namely; particles and change of state; conservation of mass (both taught commonly to 11 - 14s as part of the general science curriculum); chemical bonding; mole calculations; and combustion reactions (taught to 14 – 16s as part of a specialist chemistry curriculum). These concepts were selected because they are taught universally in all state (publically-funded) schools to all students.

Methodology

The study adopts mixed methods procedures (Meriam & Associates, 2002). Data are presented quantitatively, but classic content analysis procedures (Ryan & Bernard, 2000; Denzin & Lincoln, 2000) were used to establish coding schemes for responses to diagnostic probes. Data were collected using one probe set and were obtained from PSTs in one institution, so the study must be regarded as exploratory.

Background data were collected, coded and reported in Table 1 above. All data were collected at the start of the teacher education programme prior to PSTs receiving any science methods instruction or school placement, thus allowing opportunities for development of CCK in the light of responses. PSTs responded to a written questionnaire (summarised in Appendix 1) comprising 28 established diagnostic components (Barker, 1995) organised in five chemistry concept areas, namely *Particle theory and Changes of state*, *Conservation of Mass*, *Chemical Bonding*, *Mole calculations* and *Combustion reactions*. Each area comprised named questions, some sub-divided into component

probes. At the time of devising, the questions were validated by discussion with chemistry education colleagues, subjected to a pilot study and revised accordingly (Barker, 1994; Barker & Millar, 1999; 2000).

PSTs' responses were anonymised, then coded using coding schemes developed by classic content analysis procedures (op cit). The procedure involved sorting then grouping responses to separate "most scientifically accurate" from those which were incorrect, demonstrated misconceptions, or included no components of the scientifically accurate answer. Some "middle ground" responses in between these extremes were found. These varied for different questions. For example, some responses to calculations probes gave answers close to the correct answer, or a good estimate. Others showed evidence of understanding relevant concepts, but missed the central point required by the scientifically accurate answer. Procedurally, each coded response type was given a number. "1" was used to represent the best, most scientifically accurate answer reasonable to expect from science graduates. "7" was used for null and "8" for uncodeable responses. Probes generated different numbers of correct/accurate, middle ground and incorrect responses, so the number range used differed. The reasoning used to code responses to *Methane molecules*, which yielded thirteen coded response types (shown in Table 2), illustrates the methods applied.

[Insert Table 2 about here]

Similar responses were grouped and coded using the numbers shown. A summary response was created for each group. Group 1 responses are regarded as "correct" and are listed in Table 3. Group 2 responses, while not incorrect, do not indicate understanding of energetics and / or stability conferred by the CH₄ arrangement. All other responses were regarded as incorrect. Group 3 responses

imply formation of a molecule relies on the first-named element only. Anthropomorphic responses were coded separately as “4”. These two groups were the most frequent incorrect responses, and are listed in Table 4. Other, less frequent misconceptions or incomplete responses were: group 5 responses, which described incorrect particles forming a methane molecule, such as ions, or “4 hydrogen molecules”; group 6 responses, which used advanced chemical terminology descriptively, avoiding an explanation; and group 9 answers, which stated words to the effect “it just is like that”.

Proportions of PSTs giving scientifically correct (Table 3) and the most common partially incorrect/ misconceptions-type responses (Table 4) are shown. Space limitations mean that only the most frequently occurring misconceptions are listed. Other, less frequent responses are discussed where appropriate. Approximately 20% of responses to all questions were dual-coded by an experienced science educator colleague with expertise in chemistry. Inter-coder reliability was approximately 85%.

The second stage involved more detailed quantitative analysis (Black, 1999). PSTs' code numbers for all probes were entered into a database using Statistical Package for Social Sciences (SPSS) version 17.0. To arrive at scores for the concepts shown in Tables 5 and 6, codes for each part of every probe were re-coded to a three-component scale, “1” representing “correct”, “0” representing “incorrect” and “sysmis” (system-missing) for no response or uncodeable responses (numbered 7 and 8 throughout). Coding uncodeable responses as “system-missing” rather than “incorrect”, allowed for the possibility that a respondent may have misinterpreted a question, rather than misunderstood the chemical concept under test. Appendix 1 shows the number of question parts comprising the maximum scores in each concept area.

Decisions were made about which responses should be re-coded as “correct” or “incorrect” for each probe. For example, the scientifically accurate explanation to *Solution*, “Mass does not change when a solid dissolves in water” (Table 3) was expressed in four different ways, so four responses were all re-coded 1. These were: “the law of mass conservation states that mass cannot be lost” (formal conservation statement); “the number of particles remains the same, so mass cannot change” (particle reference); “sugar dissolves but the mass remains unchanged” (non-specific mass is constant statement) and “ $200 + 50 = 250\text{g}$ ” (numerical expression). Four responses were re-coded “0”. These were: “mass lost because particles mix”; “mass gained because sugar becomes more dense”; “mass is lost due to evaporation” and “mass is lost as a new compound forms”. All re-codings were discussed and confirmed with an experienced fellow science educator with expertise in chemistry. Scores for each concept were totalled for each PST. Tables 5 and 6 show PSTs’ scores for each concept, together with maximum possible scores, grouped by subject specialist cohort. Cronbach’s alpha values are 0.826 for the whole test and 0.667 (*Particles and Changes of state*); 0.723 (*Conservation of mass*); 0.521 (*Chemical bonding*); 0.590 (*Mole calculations*) and 0.608 (*Combustion reactions*). Mean inter-item correlations are 0.150 (Whole test), and 0.176, 0.330, 0.181, 0.323 and 0.336 respectively.

Table 5 shows mean scores achieved by biologists, chemists and physicists in all five concepts. Rigid scoring and low maximum numbers render percentages not useful, so raw scores are reported. One-way between-groups analyses of variance (ANOVA) explored significant differences in scores between the three cohorts in each concept area and for the whole questionnaire. Post-hoc comparisons using Tukey’s Honest Statistical Difference (HSD) showed significant differences between specialist subject cohort pairs, and are reported where these occur (Table 5). Effect sizes using eta squared were calculated and are reported below.

Recruitment of disproportionately more graduates with biology backgrounds (Table 1) led to

their outnumbering physics and chemistry specialists (145, compared to 76 chemists and 44 physicists).

To control to some extent for differences in sub-cohort size, each physicist, as the limiting cohort, was matched with a chemist and a biologist classified in the same age band, with the same degree classification and with/without a higher degree. Gender was not matched. This generated 44 triads each comprising one physicist, biologist and chemist. Mean concept area scores and total scores achieved by matched triad PSTs are given in Table 6, with statistically significant differences calculated as described above.

Findings

An Overview of PSTs' Chemistry Content Knowledge About Five Chemistry Concepts

Table 3 summarises proportions of PSTs giving scientifically correct responses to diagnostic questions in Appendix 1. Table 4 shows the main partially correct/ incorrect answers found.

[Insert Tables 3 and 4 about here]

Particle theory and change of state.

Responses to *Atoms* (Table 3) reveal most PSTs hold secure understandings of some properties of a single copper atom. A misconception held by about 32% (Table 4) is that a single copper atom is coloured. About 22% gave an explanation indicating they transferred macroscopic properties to a single atom.

Flask provided three separate outlines of conical flasks each with a stopper. PSTs were asked to complete the drawings to show their ideas about gas properties. Responses show 98% held the basic understanding that gas particles distribute evenly within a sealed vessel (Table 3, *Flask A*). Diagrams relating to *Flask C* showed about 9% acknowledged vapour pressure, drawing particles above the liquid phase. That nothing, space or a vacuum exists between gas particles was reported by about 52%.

Conversely, Table 4 confirms vapour pressure seems poorly understood, as about 49% omitted particles above the liquid from their *Flask C* drawings. A further 27% used a line to represent a phase barrier, as well as drawing particles, suggesting they confused macroscopic text-book style images with microscopic representations. About 12% argued forces or bonds exist between gas particles. These responses, while not wholly incorrect, suggest over-interpretation of the question. Table 4 also shows a further 10% suggested air was between particles.

Boiling probed understandings of liquid-gas-liquid state changes in water. Precise responses were given by about 48% of PSTs (Table 3). About 23%, connected loss of energy with the gas-liquid state change. Table 4 indicates about one-third responded ambiguously, suggesting “air” or “oxygen” to the “bubbles” question. 11% think water molecules break up when water boils, generating hydrogen and oxygen. The second part of *Boiling* did not probe precisely if PSTs may think water molecules reform from constituent gases as they cool, although nearly half (48%, Table 3) gave the response “gas cools on the window..”.

Conservation of mass in closed system reactions.

Mass conservation during dissolving appears well-understood (Table 3). Around 70% gave correct responses to *Phosphorus* and 60% to *Precipitation*. Respondent fatigue (the questions were adjacent) may have caused fewer correct responses, as PSTs treated all three questions as identical. Some PSTs misunderstood the chemical events in the probes, for example, reasoning a gas is produced so mass decreases (8% to *Solution*, 22% to *Phosphorus* and about 20% to *Precipitation*). Gases are thought commonly to be produced in any chemical reaction/event (Barker & Millar, 1999; Author, 2004), so a “mass decrease” response to *Solution* and/ or *Precipitation* does not discount conserving mass, as any gases would leave the reactions. Contrastingly, a “mass decrease” response to

Phosphorus, which describes a closed system, may indicate a misconception about mass and density, i.e. that a gas “is lighter” than liquid or solid. Similarly, the “greater mass” response (13% to *Precipitation*) arises from thinking solid “is heavier” than liquid. Exploring consistency of these responses shows that three biologists and three chemists gave mass-density explanations to *Phosphorus* and *Precipitation*; 17 (6 biologists, 8 chemists, 3 physicists) chose “less than” in response to *Phosphorus* and “greater than” to *Precipitation*. These figures suggest few PSTs utilise a consistently faulty mass-density model, but around 10% reason this way in specific circumstances.

Table 4 shows that the misconception mass is lost by conversion to energy is a common response. Question “noise” in *Phosphorus*, namely a sealed flask and the Sun, may have invoked these “energy transfer”-type responses. 9 PSTs (5 biologists, 4 physicists) gave “energy loss” responses to *Precipitation*. Technically a tiny amount of mass does change, but this is irrelevant to the main point.

Chemical bonding.

Table 3 shows low numbers of PSTs gave correct responses to any probe, suggesting significant weaknesses are commonplace. The mode score was one from five, achieved by 98 PSTs (37%).

Methane molecules and *Sodium and chlorine* explore understanding of the link between energy release and stability associated with covalent and ionic bond formation respectively. Although about 14% answered *Methane molecules* stating that CH_4 was the most stable arrangement (Table 3), 28% responded “satisfying valencies” was responsible. This is not incorrect, but is a descriptive, not explanatory response. Similarly, about 6% answered *Sodium and chlorine* correctly, while 20% stated the reaction between sodium and chlorine is “exothermic” without noting this meant energy is released. A further 23 mentioned electron transfer occurring, but did not say how.

Chlorides and *Hydrogen chloride* expose weaknesses in understanding connections between bond type and physical properties. About 16% showed knowledge of the role played by intermolecular

bonds (Table 3, *Chlorides*). Around 10% gave the precise answer “hydroxonium ions” (*Hydrogen chloride (Particles)*, Table 3). The “displacement reaction” response (54%, Table 3) was accepted as the best answer to *Hydrogen chloride (Reaction)*. This term is taught as an explanation of metal / acid reactions. However, the probe did not reveal if PSTs understood its meaning – anecdotally, “displacement” is taught as “swapping partners”, not as separate microscopic entities reacting. Another partially correct answer that might obscure misconceptions was given by 32%, who responded magnesium “reacts with the acid”, “replaces the hydrogen”, or with a correct symbols equation representing the reaction.

Table 4 shows many PSTs have poor understanding about aspects of chemical bonding probed here. *Methane molecules* reveals about one-third think the first element in a formula, carbon in this case, is responsible for bond formation, actively seeking bonding “partners”. Anthropomorphic reasoning, for example, “carbon *wants* to form bonds”, was used by about 7%. In responding to *Chlorides*, PSTs twisted information in different directions, explaining that “covalent bonds are weaker” or arguing they were “stronger” (Table 3) than ionic bonds.

The probe *Sodium and chlorine* did not refer explicitly to chemical bonds, so the extent to which respondents perceived the described event in microscopic and/ or bond formation terms cannot be gauged easily. Many restatements of the question (Table 4, “are reacting”, 35%) were found, showing many PSTs do not automatically use particle ideas. 46 PSTs gave responses indicative of misconceptions: 19 stated the reaction was “endothermic”; 11 “a covalent compound was formed”; and 16 used faulty particle ideas, such as anthropomorphisms, stating ions were “unstable”, or electrons were “exchanged”.

PSTs exhibit poor understanding of dissolution of covalent molecules in solution. 40 (15%) said hydrogen chloride molecules are present in hydrochloric acid. 104 (39%) suggested hydrochloric acid

comprises chemical elements, most often hydrogen, chlorine and oxygen. The presence of hydrogen chloride molecules in solution is carried into reasoning about how the acid reacts with magnesium. 15% (Table 4) implied adding magnesium meant “swapping partners” with chlorine in hydrogen chloride molecules, while 13% (Table 4) suggested “hydrogen ions” bond together to form hydrogen gas.

Mole calculations.

Table 3 shows a majority answered *Carbon* correctly. To get the correct answer addition of two numbers given in the probe was required, so respondents may have guessed. Responses to *Power Station* and *Iron sulphide* give more reliable indications of PSTs' understanding. *Power Station* uses the same reaction as carbon, but requires conversion of a large, metric unit mass value, 1000 tonnes, into moles. 23% gave correct answers (Table 4), while 18% estimated 3000 – 5000 tonnes. *Iron sulfide* required respondents to reason excess sulfur would result, with two moles of iron sulfide when two moles of iron and more than two moles of sulfur react. About 31% gave fully accurate responses (Table 4), while about 9% noted only “excess sulfur”.

PSTs' incorrect responses to *Carbon* showed over-complications, with about 12% calculating responses such as 56 g, 176 g, 172 g or 21 g. In responding to *Power Station*, 21 PSTs (7.9%, Table 4) suggested less than 1000 tonnes. About 16% stated only 192 g of iron sulphide resulted, missing excess sulfur.

Combustion reactions.

Responses show use of macro- rather than micro-scale knowledge. Table 3 shows about 41% responded correctly to *Petrol (Mass)*, stating the mass of exhaust gases would be greater than the petrol starting mass. *Petrol (Explanation)* was answered correctly by 38% who noted a combustion

reaction occurred so the mass of oxygen gas was included. Correct responses to *Methane* were less frequent. Table 3 shows 16% responded in terms of bond breaking to *Methane (Spark)*. About 19% (Table 3) noted bond formation releases energy in responding to *Methane (Energy)*. 36% of chemists (27) gave this response, but only 12 biologists (8% of the cohort) and 11 physicists (25%) did so.

Table 4 indicates about 26% conserved mass of petrol, missing the oxygen mass in exhaust gases. About 16% (41 PSTs) gave “what goes in must come out” type explanations. Around 24% (Table 4) gave non-conservation type responses. Table 4 shows two main misconceptions: mass is lost because petrol is used up (about 11%, 31 PSTs), or converted to energy to move the car (8%, 22 PSTs). The “mass lost” responses included explanations, such as petrol was “burned”, “vaporised” or “gas weighs less than liquid petrol”. Eight physicists stated “ $E=mc^2$ ”.

Two different incorrect responses to *Methane (Spark)* were common: 67 (25%,) stated “activation energy”, suggesting confusion with kinetics; and 73 PSTs stated reaction “initiation” or “ignition”. About 8% (Table 4) thought the reaction was endothermic, misunderstanding its nature. The response “the spark provided a ‘catalyst’”, also indicates confusion with kinetics. This was expressed by 15. About 52% (Table 4) of PSTs misunderstood the energy source. The most frequent, given by 31%, is that energy is released when bonds break. This may arise from recalling the taught notion that chemical bonds “store” energy, and/or “fuels are energy stores”. This is an example of a rote learned idea, which represents a partial truth. Thinking of chemical bonds in this way means it is very difficult to understand more complex ideas presented in more advanced chemistry, such as calculations involving applications of Hess’s law and Born-Haber cycles. Others named specific substances, carbon, oxygen or air as the source of energy (13%) or said the “flame”, “reaction” or “heat energy” (8%).

PSTs’ misconceptions of chemistry concepts: summary.

Overall, these data indicate support for the hypothesis that PSTs have misconceptions about chemistry topics. Many misconceptions match those of 15 year old school students, and may be the best answers these graduates can produce, based on recall of high school chemistry. PSTs with chemistry backgrounds appear to have more secure understanding than those with biology- and physics-oriented degrees. While this may be unsurprising, these data represent a systematic analysis of coded responses which could be repeated for other graduate populations. These data also afford direct comparison between graduates of different disciplines, as shown next.

Differences in Chemistry Content Knowledge Between Chemists, Physicists and Biologists

Table 5 shows mean scores achieved by biologists, chemists and physicists in the five chemistry concept areas. Significant differences are indicated at the 0.05 level (see *Methodology*) between subject specialist pairings. No significant differences were observed between the three specialist cohorts in correct responses to *Particle theory* and *Changes of state*

[Insert Table 5 Here]

or *Conservation of Mass* questions, suggesting all have similar levels of understanding. Note these topics are taught to 11 – 14s. Hence, data indicate PSTs are equipped to teach these topics. No comment is made as to the adequacy of their subject background for teaching.

The more advanced chemistry topics, *Chemical bonding*, *Mole calculations* and *Combustion reactions* show significant differences between specialist subject cohort pairings. Table 5 shows chemists perform significantly better than both physicists and biologists in all three. Physicists also out-perform biologists in *Mole calculations*. Effect sizes (eta squared) were moderate to large (Cohen, 1988): 0.106 for *Chemical bonding*; 0.059 for *Mole calculations* and 0.103 for *Combustion reactions*.

Table 5 also gives the mean total scores for the three cohorts. Chemists out-perform their

biologist and physicist counter-parts, scoring significantly better than both (effect size 0.064).

Together, these data support the hypothesis that chemists' misconceptions about these chemistry topics are less extensive than those of PSTs with biology or physics backgrounds. However, these figures are based on calculations using specialist subject cohorts of differing sizes. Table 6 presents mean score data from matched PST triads.

[Insert Table 6 Here]

The mean scores of chemist and biologist PSTs used in the triads are higher than those of the whole specialist subject cohorts shown in Table 5. This generates changes to the one-way ANOVA results pattern, so besides *Particle theory and Change of state* and *Conservation of mass*, no significant differences are found in mean score responses to *Mole calculations*. Significant differences remain for *Chemical bonding*, and *Combustion reactions*, confirming chemists' superior understanding.

Discussion

Responses to these questions show well-qualified, academically able novice teachers hold some significant misconceptions of basic chemical concepts likely to constrain development of PCK that promotes scientifically accurate learning in their students. These include: "energy is released when bonds break"; "carbon is responsible for bond formation"; "hydrogen and oxygen are produced when water boils"; "covalent bonds are weaker/stronger than ionic bonds"; and mass/density confusion. A tendency towards use of macro-scale, not micro-scale knowledge is apparent, shown by use of general phrases, such as "sodium and chlorine are reacting"; "gas cools on the window"; "valencies are satisfied"; and "the spark ignites the gases". Although these appear as plausible statements, all of them miss the central chemistry concept, and may arise from how PSTs were taught in school. More specifically, responses mentioning particles do so in faulty

language, such as “air is between gas particles”; the anthropomorphism “carbon atoms want to form bonds”; or by attributing macro-scale properties to particles, (“a copper atom is colored”). Data suggest as many as 10% of PSTs lack secure understanding of the particle model. Two of the “harder” topics, *Chemical bonding*, and *Combustion reactions*, normally taught to 14 – 16s, show biologists hold much weaker knowledge than chemists and physicists. This has consequences for chemistry being taught by non-specialists. Implications arising from these points are discussed.

First, as the literature review indicates, teachers with weak CK tend also to demonstrate weak PCK. If (or when) PSTs teach these concepts, they will need to rely on rote learned phrases, often regurgitated in examinations, for their conceptual framework. PCK allied to these will be similarly constrained, meaning that students will be encouraged to rote learn the appropriate phrases, rather than to ask challenging questions, or to develop secure understanding. As indicated during the data presentation, failure to understand these basic concepts means students will struggle to comprehend inter-connecting, more advanced ideas. This is not a position from which to generate high quality teaching and learning.

Second, let us consider the origins of these ideas. These are known to be varied: Taber & Tan (2011) identify intuition, the life-world, language, and teaching as possibilities. We cannot discount the first three as accounting for at least some of the incorrect responses reported, but teaching is crucial here. At least some of these answers arise because curriculum documents do not consistently encourage teaching of ideas central to understanding a concept – at least, in the UK, where most of these PSTs were educated, rote-learned general phrases are tested in examinations, not underpinning specifics. Also, responses may arise because some PSTs were taught by non-chemists, whose PCK was limited by their own content knowledge weaknesses. Taber & Tan (op cit) suggest, “*teachers’ own alternative conceptions make up one significant factor in the development of some alternative*

conceptions in their students" (p 264, Taber & Tan's italics). These data indicate that given their poor knowledge levels, and consistent with studies reviewed above, biologists may be especially susceptible to perpetuating generalizations and skirting over difficulties with certain concepts. An implication arising is that we need to provide teacher education that breaks this cycle.

Third, given this position, we need to consider how to correct graduates' misconceptions. Eilks & Byers (2009) provide suggestions that may support teacher educators in achieving this. As Arzi & White (2007) show, with time, curriculum knowledge, rather than CK dominates a teacher's thinking and planning. Other researchers cited above show that experience is no guarantee of excellence. Although these PSTs went on to experience a university-based programme that attempts to raise the quality of their CK systematically in chemistry, biology and physics, through sessions that taught concepts including reference to specific misconceptions, any systematic testing of knowledge was left to PSTs themselves as individuals. This falls short of a systematic approach to diagnosing and "treating" PSTs' misconceptions about science concepts. Thus, university-based teacher education systems are imperfect. Taber & Tan (2011) point out that flawed teacher knowledge is a likely contributor to the kinds of responses this study reveals. The PSTs themselves were taught flawed knowledge, which they will, without malice aforethought, perpetuate in their students. For most of the last forty years teachers have been trained through postgraduate programs at UK universities, and prior to that, teacher education colleges. This system has not produced teachers with CK or PCK enabling them to teach in ways that minimize chemistry misconceptions. Recruitment patterns mean that a majority of PSTs are biologists who, at least in this study, demonstrate relatively weak CK for these concepts compared to their physicist and chemist counterparts. These facts point to failures in current teacher education methodology, as the PSTs must have learned their science by teachers educated in the current, prevailing system. Assuming the recruitment position remains unchanged, there is a need to

ensure graduates are properly equipped to teach chemistry. Ball & Forzani (2010) comment, "Students must have teachers who are prepared to help them learn, not beginners who are struggling themselves" (p 12).

There is a move in some countries towards extending teacher education methodology to schools, rather than universities, as indicated in the introduction. Burn, Childs & McNicholl's work (2007) may inform a model for school-based teacher education. They tracked how PSTs on placement in two school science departments developed their PCK. These schools offered professionally rich, collaborative environments in which discussions could readily take place surrounding CK, and other aspects of SMK and PCK. The authors note, though, that even in potentially productive surroundings the issue of how to "enable student teachers to access experienced teachers' professional craft knowledge, which is implicit and difficult to articulate fully" (p 433) was not truly resolved. A PST needed to be alert to opportunities, naturally questioning, able to pick up what was being said and know how to apply this to his/her own work. The success of a school-based programme for developing high quality science teaching requires that a systematic method for elucidating and addressing PSTs' misconceptions is required. This will involve experienced teachers questioning their understandings, addressing any weaknesses and adopting teaching practices that help students learn chemistry concepts meaningfully, rather than by rote-learning general phrases. To date, there is no evidence that such a system exists: experienced teachers in schools are, as Arzi & White (2007) indicate, bound to curricula, school context and general pedagogical issues. CK and precise PCK are framed and limited by these concerns, perceived as over-riding and critical to a school's daily functions. In practice, PSTs with a variety of scientific backgrounds come forward for teacher education. These graduates may have mastery over their degree subjects, but these backgrounds do not form the everyday "stuff" of a

school science curriculum. Even the most inviting school environment for teacher education is unlikely to allocate sufficient time to fully compensate for CK weaknesses arising amongst PSTs with such varied scientific backgrounds. There is a danger, therefore, that school-based teacher education leaves PSTs under-prepared for the realities of classroom life (Houston, 2008). They may be limited, as Lock et al (op cit) suggest, to “getting by” rather than educating students. The diagnostic probes utilized here offer a starting point towards a means of resolving this. They are easily administered and may be coded clearly to indicate the kinds of understandings and misconceptions held by teachers and school-students alike. Prompt diagnosis is a means to effecting a cure.

Independently of the methodology employed to educate teachers, PSTs need to be made aware of misconceptions in chemistry, and be taught scientifically correct understandings likely to lead towards effective PCK prompting students' learning. Coll & Treagust (2003) point to requirements such as understanding the relationship between macro, micro and symbolic representations, use of mental models and visualizations of chemical events. These are likely to have meaning only when teachers' CK is secure. Anecdotally, the author has witnessed profound changes in experienced teachers' PCK for teaching chemistry concepts on analysing data collected from students they have taught that shows misconceptions such as those reported here. As a direct consequence, many have sought clearer and better CK to prepare better PCK that generates successful learning.

This study is inevitably limited, and of an exploratory nature, as data are collected from one institution, by one means, and about a relatively small range of chemistry concepts using probes subject to critique. Nonetheless, they offer the novelty of a detailed, consistent, plausible picture of PSTs' understandings of chemistry concepts taught across the 11-16 age range, in the same study. The quality of PST chemists', biologists' and physicists' CCK on commencement of a university-based science teacher education programme clearly differs, indicating significant weaknesses within the

numerically dominant specialist biologist sub-cohort. Positively, however, the study offers the beginnings of work towards a systematic, quantitative, diagnostic strategy for testing CK in PSTs. Since this study was undertaken, work has continued to adapt the probes to a multiple-choice format, with a view to making a test available online (Kind & Clark, 2013, in preparation). The hope is that this work will contribute to teacher education methodology that helps prevent perpetuation of a cycle of poor understanding and low student achievement in this major science.

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Characteristic	PSTs by specialist science subject							
	Whole sample		Biologists		Chemists		Physicists	
Number of PSTs	265		145 (54.7)		76 (28.7)		44 (16.6)	
Gender	144 (54.3)	121 (45.7)	93 (35.0)	52 (19.6)	41 (15.5)	35 (13.1)	10 (3.8)	34 (12.8)
Age								
21 – 25	97 (36.6)	74 (27.9)	67 (25.3)		22 (8.3)	12 (4.5)	8 (9.4)	25
26 – 30			37 (14.0)		9	7		
31 – 35	24 (9.1)	21 (7.9)	14 (5.3)	10 (3.8)	3	7	1	4
36+	9	10 (3.8)	6	2	7	9	0	1
	14 (5.3)	16 (6.0)	6	3			1	4
Degree class*								
1st	16 (6.0)	15 (5.7)	8	2	8	4	0	9
2:1			53 (20.0)		12 (4.5)	9	2	7
2:2	67 (25.3)	45 (17.0)	29 (10.9)		16 (6.0)	14 (5.3)	6	15 (5.7)
3rd / pass			26 (9.8)	18 (6.8)	4	4	1	2
Other / Not stated	48 (18.1)	47 (17.7)			1	4	1	1
	8	8	3	2				
	5	6	3	1				
Higher degrees	27 (10.2)	27 (10.2)	14 (5.3)	9	12 (4.5)	14 (5.3)	1	4
Other relevant training			0	0	1	0	1	0
	2	0						

*UK degree classes equate to US GPAs broadly as follows: 1st = >3.80; 2:1 = 3.30 – 3.79; 2:2 = 3.00 – 3.29; 3rd / pass no GPA equivalent

N= 265

Figures in each column are presented as female, male

Figures in parentheses are percentages of the whole sample, calculated for values >= 10

Table 1: Pre-service science teachers' (PSTs) backgrounds: gender, age, degree class, higher degrees and specialist science subjects

Response	Number	Summary response
CH ₄ represents the most stable arrangement	1	CH ₄ represents the most stable arrangement for atoms in a methane molecule
CH ₄ is the most energetically favoured arrangement	1	
The formula satisfies the valencies of carbon and hydrogen	2	The formula depends on satisfying valencies of both elements
The formula gives carbon and hydrogen full outer electron shells	2	
The valency of carbon is satisfied	3	Carbon atoms only are responsible for bond formation
Carbon makes 4 bonds	3	
Carbon has a full outer electron shell	3	
Carbon atoms want to form 4 bonds	4	Anthropomorphic response
Carbon and hydrogen form ionic bonds	5	Incorrect particle response
4 hydrogen molecules are involved	5	
The methane molecule is saturated in this arrangement	6	Description mis-applying chemical terminology
The methane molecule is hybridised in this arrangement	6	
No response	7	
Uncodeable responses	8	
Methane always has the formula CH ₄	9	"It just is like that"

Table 2: Coding and summarising responses to *Methane molecules*

Chemistry concept area	PST subject specialist groups			
	Maximum possible score	Chemists N= 76	Physicists N=44	Biologists N= 145
Particle theory and Changes of state	10.00	6.51	6.32	5.94
Conservation of mass	6.00	4.57	3.77	4.40
Chemical bonding	5.00	2.28**	1.66	1.35
Mole calculations	3.00	1.99*	2.07*	1.51
Combustion reactions	4.00	2.37**	1.52	1.36
Total test score	28.00	17.71**	15.34	14.56

* One-way ANOVA with post-hoc comparison using Tukey HSD shows significant differences between chemists and biologists and physicists and biologists, at 0.05 level

** One-way ANOVA with post-hoc comparison using Tukey HSD shows significant differences between chemists and biologists and chemists and physicists, at 0.05 level

Table 5: PSTs' mean scores in five concept areas of chemistry, and mean total test scores

Chemistry concept area	Maximum score	Mean scores of PSTs in matched triads		
		Biologists N= 44	Chemists N= 44	Physicists N=44
Particle theory and Changes of state	10.00	6.48	6.56	6.32
Conservation of mass	6.00	4.50	4.45	3.77
Chemical bonding	5.00	1.45	2.43 ⁺	1.66
Mole calculations	3.00	1.84	2.14	2.07
Combustion reactions	4.00	1.75	2.45 ⁺	1.52
Total test score	28.00	16.02	18.04*	15.34

*One-way ANOVA with post-hoc comparison using Tukey's HSD shows significant differences between *chemists and physicists* at 0.05 level

+One-way ANOVA with post-hoc comparison using Tukey's HSD shows significant differences between *chemists and physicists* and *chemists and biologists* at 0.05 level

Table 6: Matched triad PSTs' mean scores in five chemistry concept areas, and mean total scores

Appendix 1 Diagnostic chemistry content knowledge questions

Chemistry concept area	Question Name	Content	Score
Particle theory and change of state	Atoms	Is an atom of copper... malleable? ductile? coloured? Explain your answer	1 1 1 1
	Flask	Draw particles in the flask outlines provided to show:-	
	A	a flask of air at room temperature	1
	B	the same flask with air removed and	1
	C	the same flask cooled to liquefy the air (Outline drawings of three sealed flasks were provided) Explain what is between the particles.	1
	Boiling	What is in the bubbles in boiling water? Explain how condensation forms on a window pane.	1 1
	Total score for this concept area		10
Conservation of mass	Solution	Is the mass of a solution the same, greater or less than the mass of solute + solvent? Explain your answer	1 1
	Phosphorus	A reaction occurs when phosphorus and water are placed in a closed flask which is heated by the Sun. Is the total mass afterwards the same, greater or less than the starting mass? Explain your answer	1 1
	Precipitation	Two clear, colorless solutions are combined. A precipitate forms. Is the mass after the reaction the same, greater or less than the starting mass? Explain your answer	1 1
	Total score for this concept area		6
Chemical bonding	Methane molecules	Why does methane form compounds with formula CH ₄ , not CH ₃ , CH ₂ or CH?	1
	Chlorides	Explain why the vapor above a mixture of titanium(IV) chloride and magnesium chloride comprises titanium(IV) chloride only.	1
	Sodium and chlorine	What is happening when hot sodium is lowered into a gas jar of chlorine and white sodium chloride is spattered on the inside of the jar?	1
	Hydrogen chloride	What particles are present in hydrochloric acid? Explain how hydrogen gas forms when a piece of magnesium metal is lowered into hydrochloric acid.	1 1
	Total score for this concept area		6
Mole	Carbon	Estimate the mass of carbon dioxide produced when 24 g carbon is burned in 64 g oxygen gas. (A _r values and equation were	1

calculations		provided)	
	Power Station	Estimate the mass of carbon dioxide generated by a power station burning 1000 tonnes of coal.	1
	Iron sulfide	What would you get when 112 g iron and 80 g sulfur are made to react? (The equation showing 56 g iron and 32 g sulfur reacting was provided)	1
	Total score for this concept area		3
Combustion reactions	Petrol	Is the mass of exhaust gases produced from 50 kg petrol the same, greater or less than the mass of petrol? Explain your answer.	1 1
	Methane	Why is a spark or match needed to get methane burning? Where does the energy come from when methane burns? (The equation for combustion of methane in oxygen was provided)	1 1
	Total score for this concept area		4